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XVII. *Comparison of Magnetic Disturbances recorded by the Self-registering Magnetometers at the Royal Observatory, Greenwich, with Magnetic Disturbances deduced from the corresponding Terrestrial Galvanic Currents recorded by the Self-registering Galvanometers of the Royal Observatory.* By GEORGE BIDDELL AIRY, *Astronomer Royal.*

Received December 20, 1867,—Read February 6, 1868.

It would be difficult, even at this early stage in the history of the treatment of Spontaneous Terrestrial Galvanic Currents, to say how the science began*. As far as relates to my own acquaintance with it, it originated in some general knowledge of the existence, on special days, of currents disturbing practical telegraphic operations, which were soon found to synchronize with magnetic storms, and in communications with Mr. EDWIN CLARK and Mr. LATIMER CLARK, both of whom volunteered their assistance, but more particularly in conversations, and subsequently in correspondence, with CHARLES V. WALKER, Esq. On several occasions, tabular numerical statements were transmitted by Mr. WALKER to me, and copies of the Greenwich magnetic photograms were transmitted by me to Mr. WALKER; Mr. GLAISHER also went to Tunbridge several times, to discuss the subject with Mr. WALKER. It is not necessary here further to allude to the important papers in the Philosophical Transactions by Mr. W. H. BARLOW (1849) and by Mr. WALKER (1861 and 1862), or to the subsequent observations of Dr. LAMONT, except for the purpose of remarking that these philosophers possessed no means of maintaining a constant record by self-registering apparatus.

The history of the establishment of apparatus at the Royal Observatory is as follows. In my Annual Report to the Board of Visitors of the Royal Observatory, 1860, June 2, I submitted to the consideration of the Board, "It may be worth considering whether it would ever be desirable to establish in two directions at right angles to each other (for instance, along the Brighton Railway and along the North Kent Railway) wires which would photographically register in the Royal Observatory the currents that pass in these directions, exhibiting their indications by photographic curves in close juxtaposition with the registers of the magnetic elements."

The subject having been thus formally opened, and various communications having passed with Mr. WALKER as Superintendent and Engineer of the Telegraphs of the South-Eastern Railway (in which capacity Mr. WALKER has rendered very important services to the Royal Observatory), I again, on 1861, June 1, brought the matter before the Board of Visitors, in these words: "I alluded in my last Report to the possible esta-

* Allusion will be made hereafter to the paper by the late Professor BARLOW in the Philosophical Transactions, 1831, of which, however, the subject is different from that treated here.

blishment of galvanic wires which would record, perhaps upon the same photographic sheet which bears the declination and horizontal force, the magnitude and direction of earth-currents in two directions. I conceive that this may be justly regarded as an important physical experiment; and I hope to be able shortly to lay before the Visitors some details of plan, and to ask their opinion in a more precise form." The Board, after consideration of my proposals, resolved "that it be recommended to the Board of Admiralty that two lines of insulated wires be established from the Royal Observatory to the stations near Dartford and Croydon, with suitable apparatus at the Royal Observatory for the purpose of registering the intensity and direction of terrestrial galvanic currents dependent on natural causes at present obscure."

Mr. WALKER, in his paper in the Philosophical Transactions, 1861, alluded to the matter as having come before him, and as having been the subject of his Report and Estimate; and added, "I have, to a certain small extent, made progress in anticipation."

On 1861, August 14, I submitted a Memorial to the Lords Commissioners of the Admiralty on the advantage of erecting the necessary wires and recording apparatus, at an estimated expense of £250; and on August 19 I received Their Lordships' sanction to my placing that sum on the Navy Estimates for the Financial Year 1862-1863. On August 24 I made formal application to the Directors of the South-Eastern Railway for permission to place the wires on the poles of their Telegraph, and on December 20 I received their assent. The terms on which this assent was granted were most liberal; no stipulation being made except for the nominal annual rent of five shillings for the use of the poles and five shillings for the maintenance of the wires in a state of repair. And I take this opportunity of adding that, when it was found that, by the adoption of insulators of a high class, the expense was made to exceed the estimate, Messrs. SILVER, the contractors for the insulators, at once resigned all profit. The whole of the wire-work has been done at cost price.

The wires were completely established under the superintending care of Mr. WALKER about the autumn of 1862. The wire is that technically called No. 8, $\frac{1}{8}\frac{1}{4}$ inch in diameter, annealed iron wire, coated with zinc by galvanic deposit. The insulators consist each of a double ebonite cup with outer porcelain cup. From the Observatory to the Railway, the wires at different times have been led by different channels, but are now led underground. The connexions with earth have been made in various ways, but at present they are made at each of the three stations by soldering the wires to water-pipes.

The plan for forming, on a revolving cylinder (covered with photographic paper), a spot of light whose position should depend on the galvanic current passing through the wires, was arranged at the beginning of 1863. Each wire communicates with the coil of a galvanometer. It may be mentioned here that the current has proved far stronger than was anticipated. At first, a nearly astatic combination of needles was provided; it was speedily found necessary to turn the red* ends of the needles in the same direction;

* By the *red* end of a needle, I mean that end which is charged with austral magnetism, and which when the needle is freely suspended turns to the north magnetic meridian.

and subsequently the coils were reduced. At present, the entire number of turns of the wire about the acting needle of each galvanometer is 200, and the length of the acting needle is a little more than 1 inch. The needle is suspended by a human hair. A stalk below carries a small plane mirror, whose surface is about $\frac{1}{2}$ inch by 1 inch. With the assistance of cylindrical lenses, a very neat spot of light is thrown upon the revolving barrel by the following arrangement. The beam of light from the lamp falls upon a fixed vertical cylindrical lens, and is made to converge in the horizontal plane. In this state it falls on the plane mirror, converging in the horizontal plane, diverging in the vertical plane. It leaves the plane mirror in the same state, only having received the change of direction corresponding to the play of the galvanometer-magnet; and it then falls on a fixed horizontal lens, which makes it converge in the vertical plane. (This is the plane of a transverse section of the revolving cylinder, which defines the direction of the time-abscissa of the photographic curve.) A single lamp gives light for the recording apparatus of both wires.

The revolving barrels, which had been used for many years in conjunction with the self-registering magnetometers of the Royal Observatory, were of glass, selected with great care, first by Mr. BROOKE, afterwards by Mr. GLAISHER, from the extensive stock of a large manufacturer; and their circularity and cylindricity of form were almost perfect. I was desirous, however, of using for the earth-current-apparatus a barrel turned in the lathe. After endeavouring in vain to obtain glass so turned, I succeeded in procuring a barrel of ebonite, manufactured by Messrs. SILVER. The difficulty of securing this occasioned nearly a year's delay in the completion of the apparatus. Another year was added by the excavation of the Magnetic Basement in which the apparatus was to be placed, and by the caution necessary to be used while the walls were damp. Finally, the apparatus was brought into action and the records were made as a matter of routine, on 1865, April 1, and from that time the registers are almost perfect; the principal interruption being that produced by the great snowstorm of 1866, January.

The instrumental elements on which it appeared desirable to maintain a constant check are the following: the freedom of the barrel from end-shake, and the uniformity of its rotation; the zero of time on the line of time-abscissa; and the zero of galvanic measure for the ordinates. And the checks are thus made.

In regard to end-shake of the barrel, a small lamp throws a light through a definite hole in the cover of the barrel, which, as the barrel revolves, forms a photographic line parallel to the line of time-abscissa, usually called the "photographic base-line."

In regard to the uniformity of rotation, it has been the practice, since self-registering apparatus was established, to produce an interruption in the register, by stopping off the light for a few minutes, three times every day; the observer registering from the clock-dial the times of stopping and readmitting the light. For the test of circularity, this has been done on a limited number of days, six times in the day, at moments extending with approximate uniformity of intervals through the twenty-four hours.

The operation to which I have alluded, even if performed only three times in a day, when used in conjunction with pasteboard scales carefully adjusted to exhibit 24^h for

the revolution of the barrel, gives ample information whereby a time-scale can be laid down applying to every part of the photographic curve.

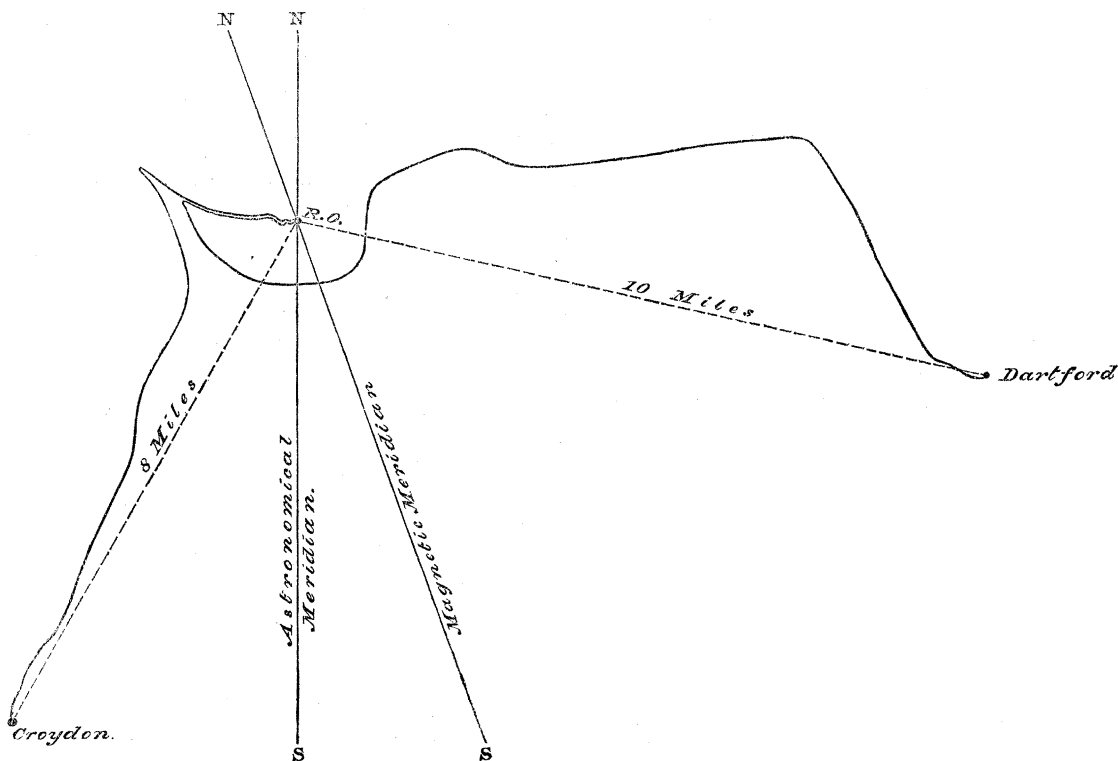
The zero of galvanic measure is obtained by simply interrupting the wire-circuit.

I desire to state that great attention has been given to every one of these adjustments, more especially to those which relate to time. At an early epoch in the comparison of the two classes of measures, it became obvious that questions of simultaneity would arise. Great care has been taken by Mr. GLAISHER in the formation and application of all the time-scales, and I am confident that I can answer for the simultaneity or non-simultaneity of the phenomena, to one or two minutes of time.

Before entering into details of our observations, I will remark that it is perfectly certain that atmospheric influences have produced no effect on our records. This appears in two ways. First, that the Croydon currents (which convey almost the whole of the terrestrial galvanism) have, at all times, an aspect totally different from that of the Dartford currents; secondly, that whenever a wire is broken, at whatever place on the wire, the galvanometer-needle then remains motionless at the zero point. In one or two instances the wire has been broken at a considerable distance from the Observatory, and has fallen so that its end lodged in the ground; and then it has conveyed a very good terrestrial current.

We thus obtain simultaneous galvanic indications from the two instruments, measurable by the parts of scales of sensibly equal value. I proceed to explain the method by which they have been treated.

From the Map which accompanies this communication, it appears that the azimuth of



the Dartford station as viewed from the Royal Observatory, measured from the magnetic

north in the direction N., E., S., W., is $122\frac{1}{4}^\circ$; and that of the Croydon station is $229\frac{1}{4}^\circ$. Let C be the measure of a galvanic current from Croydon, D that of a current of the same kind (as referred to a battery-pole) from Dartford; and assume these to be caused by a galvanic current N of the same kind towards the north, and a galvanic current W of the same kind towards the west; and that these north and west currents admit of being resolved according to the rules of resolution of mechanical statical force. Put α for the azimuth of Croydon, α' for that of Dartford. Then it is easily found that

$$W = C \cdot \frac{\cos \alpha'}{\sin (\alpha - \alpha')} - D \cdot \frac{\cos \alpha}{\sin (\alpha - \alpha')};$$

$$N = C \cdot \frac{\sin \alpha'}{\sin (\alpha - \alpha')} - D \cdot \frac{\sin \alpha}{\sin (\alpha - \alpha')};$$

which, converted into numbers, give

$$W = -C \times 0.55800 + D \times 0.68259,$$

$$N = +C \times 0.88437 + D \times 0.79218.$$

Now, upon interposing a battery in the course of each of the wires, with its graphite or copper pole towards Greenwich, it was found that, on the Croydon wire, it gave an ordinate upon the photographic sheet in the direction which we are accustomed to measure as positive; and on the Dartford wire it gave an ordinate upon the photographic sheet in the negative direction. Let C' and D' be the measured quantities; then $C' = +C$, $D' = -D$; and

$$\text{Graphite current towards } W = -C' \times 0.55800 - D' \times 0.68259,$$

$$\text{Graphite current towards } N = +C' \times 0.88437 - D' \times 0.79218.$$

Conceiving this graphite current, if it is really a terrestrial galvanic current acting on our magnetometers, to be below them, it will deflect any part of a magnet possessing red or austral magnetism to the right, estimated with reference to the direction of the current's course. Hence we obtain

$$\text{Magnetic tendency to } N = -C' \times 0.55800 - D' \times 0.68259,$$

$$\text{Magnetic tendency to } W = -C' \times 0.88437 + D' \times 0.79218.$$

It was found that when the ordinates as measured from the photographic sheet were multiplied by these factors, they gave results larger than those on the magnetometer sheets with which I desired to compare them; and, in order to diminish their magnitude, they were multiplied by 0.5437. Hence, putting $e = 0.68259 \times 0.5437$, $f = 0.55800 \times 0.5437$, $g = 0.79218 \times 0.5437$, $h = 0.88437 \times 0.5437$ (the order of C' and D' having been accidentally inverted),

$$\text{Magnetic tendency to } N = -D' \times e - C' \times f,$$

$$\text{Magnetic tendency to } W = +D' \times g - C' \times h.$$

It now became important to consider how, from the photographic curves of the Earth-currents, these Magnetic Tendencies could be most conveniently obtained. For my own

preliminary trials, I had four proportional compasses constructed by Mr. SIMMS, by means of which I took the proportional part (as expressed by the factor e , or f , &c.) of the ordinate to which that factor applied, laid it down on a new ordinate, and laid, at the top or bottom of the ordinate, the other part which was to be added or subtracted, and thus formed curves for Magnetic Tendencies without the use of any numerals whatever. But this method is not suited to a junior computer. After having satisfied myself that there was good ground for proceeding further, I arranged, for the work of the young assistants, the following process. Four pasteboard scales were prepared, with different graduations:—

“Scale E for Dartford,” with graduation $= \frac{1}{e} \times$ graduation of Horizontal-Force-Magnetometer, measuring negatively;

“Scale F for Croydon,” with graduation $= \frac{1}{f} \times$ graduation of Horizontal-Force-Magnetometer, measuring negatively;

“Scale G for Dartford,” with graduation $= \frac{1}{g} \times$ graduation of Horizontal-Force-Magnetometer, measuring positively;

“Scale H for Croydon,” with graduation $= \frac{1}{h} \times$ graduation of Horizontal-Force-Magnetometer, measuring negatively.

Then, the times for which the measures were to be taken having been previously prepared, the ordinate D' was measured with scale E, and the ordinate C' was measured with scale F; the numbers were set down in parallel columns and added together, and the sum was used to form a new ordinate of Magnetic Tendency to N. Similarly D' was measured with scale G, and C' with scale H, and their numbers were added to form a new ordinate of Magnetic Tendency to W. At every point where the zero of ordinate had been obtained by breaking the wire-circuit, the ordinate was measured in the same way.

In this manner were formed all the curves, exhibiting Magnetic Tendency to N. and W. inferred from Galvanic Measures, which I now exhibit to the Society. (Plates XXV. to XXX.)

For the other curves, that which exhibits Magnetic Force to the North is simply a copy, on an altered scale, of the record of the Horizontal-Force-Magnetometer; and that which exhibits Magnetic Force to the West is derived from the record of the Declination-Magnetometer, the angular deviations being converted into proportionate parts of horizontal force, and laid down on the same scale as the ordinates of the Horizontal-Force-Magnetometer.

The days were selected as exhibiting rather bold curves. I was prevented from taking several which I should have thought preferable, from some scruples (which afterwards proved to be entirely unfounded) about the accuracy of the time-scale.

I now proceed to remark on the comparison of the two systems of curves.

It is impossible, I think, to see these curves without being struck with their general

agreement. In particular, those which exhibit the irregularities of Northerly Magnetic Force are extremely accordant. Yet there are some minor points of discordance, both general and special, which merit most careful attention; and to these I now call the attention of the Society.

The remark of most extensive application is, that the irregularities of the curves derived from the Galvanic Currents are more numerous than those derived from the Magnetometers. I know not whether this is inherent in the nature or origin of the currents, or whether the Magnetic apparatus is less sensitive than the Galvanic apparatus.

The next remark is, that the irregularities derived from the Galvanic Currents almost always precede those derived from the Magnetometers. These intervals of time, as I have already remarked, are perfectly certain. There are a few instances (as West Force, 1867, April 8, 14^h, and June 1, 15^h 50^m; and North Force, 1867, May 28, 7^h 20^m, and June 1, 12^h and 13^h) in which the Galvanic irregularity appears to follow the Magnetometer irregularity; and a greater number, especially in the North Force, in which their coincidence of time is sensibly perfect; but in very far the greatest number, the Galvanic irregularities precede the Magnetometer irregularities. In the instance of West Force, 1866, October 4, 9^h 40^m, and probably in some others, the advance of the Galvanic irregularity is nearly half an hour.

In several instances, the proportions of consecutive rise and fall are not the same in the two systems of curves. Thus on 1866, October 4, 5^h to 6^h, the proportions are unequal for the West Force, and, in a minor degree, for the North Force. So also for the West Force, 1867, May 28, 7^h to 8^h, and June 1, 10^h to 11^h. In this element, as in the times, the accordance is better for the North Force.

On 1867, June 7, 3^h, there is a remarkable salience of the Galvanometer curve for the West Force. Mr. GLAISHER suggests an explanation of this which I believe to be correct. The circuits had been interrupted in order to make time-marks, and the wires had probably taken a galvanic charge, which apparently burst out with great force when the circuits were restored.

On 1867, April 4, West Force, there is discordance which is completely explained by ordinary acceleration of Galvanic results and inequality in the proportions of rise and fall.

On 1867, June 2, West Force, there is discordance of which it is possible the explanation may be different. The day was the Sunday following the Visitation, and it is possible that the instruments may have been disturbed, and that the disturbances may not have been corrected. [It is now believed that the movement of the Declination Magnetometer was impeded by contact with its box.]

After all attention has been given to these points, I think that, on repeatedly examining the agreements of the two systems of curves, it is impossible to avoid the conclusion that the magnetic disturbances are produced by terrestrial galvanic currents below the magnets. Yet there remain some points to be explained before we can state that galvanic currents, as we observe them, will account for all that we observe in the magnetometer records.

One point, of considerable importance, is the relation of the new curves to their zeros. I have stated that the readings by means of Scale E, Scale F, &c. have been taken in the same way for the zeros of galvanic ordinates as for the points of the curves; and, by means of these, zero-lines have been laid down on the diagrams. From general inspection of these, it would seem that, on the days of magnetic storms, the North Force, as shown by the galvanic currents, is on the whole increased. But I believe that in all examinations of magnetometer results for North Force during magnetic storms, and certainly for those in the Royal Observatory (see the Analysis of 177 Magnetic Storms, *Philosophical Transactions*, 1863) it is found that the North Force is diminished. I cannot at present explain this discordance.

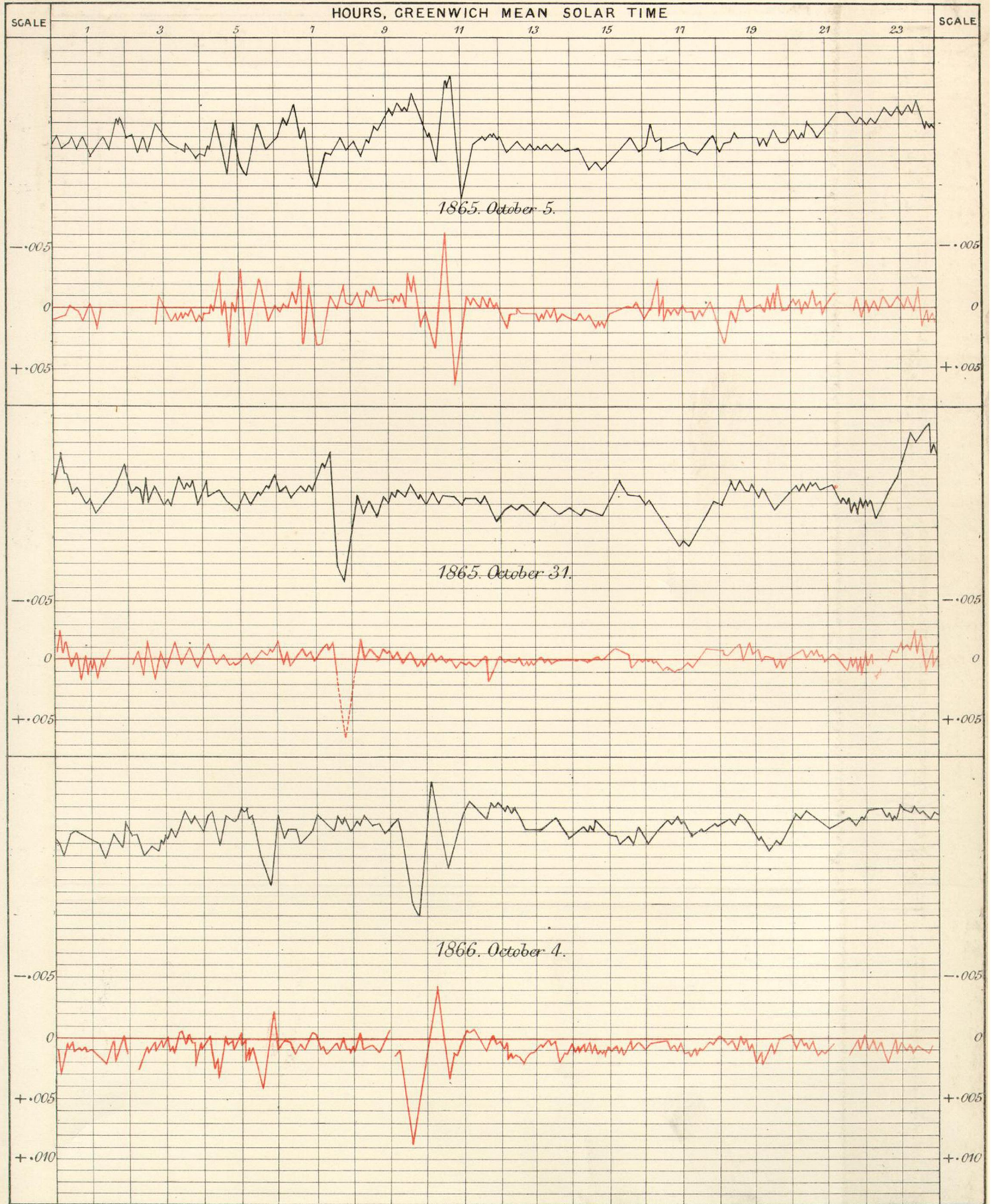
The other discordances, both of time and measure, may not improbably depend on the following circumstance. The south-western (Croydon) wire is entirely south-west of the Royal Observatory; and the south-eastern (Dartford) wire is entirely south-east of the Royal Observatory. It is probable therefore that the times and magnitudes of the terrestrial currents which pass through these wires, correspond rather to places near the middle of the straight lines connecting the Royal Observatory with Croydon and Dartford than to the locality of the Royal Observatory itself.

It might be a question whether, in continuing these observations, the length of wires might not be considerably reduced, and whether an attempt might not be made to give such terminations to each that the recording apparatus should be nearly in the middle of the length of each. In the actual topographical circumstances, it may not be easy to secure the latter condition.

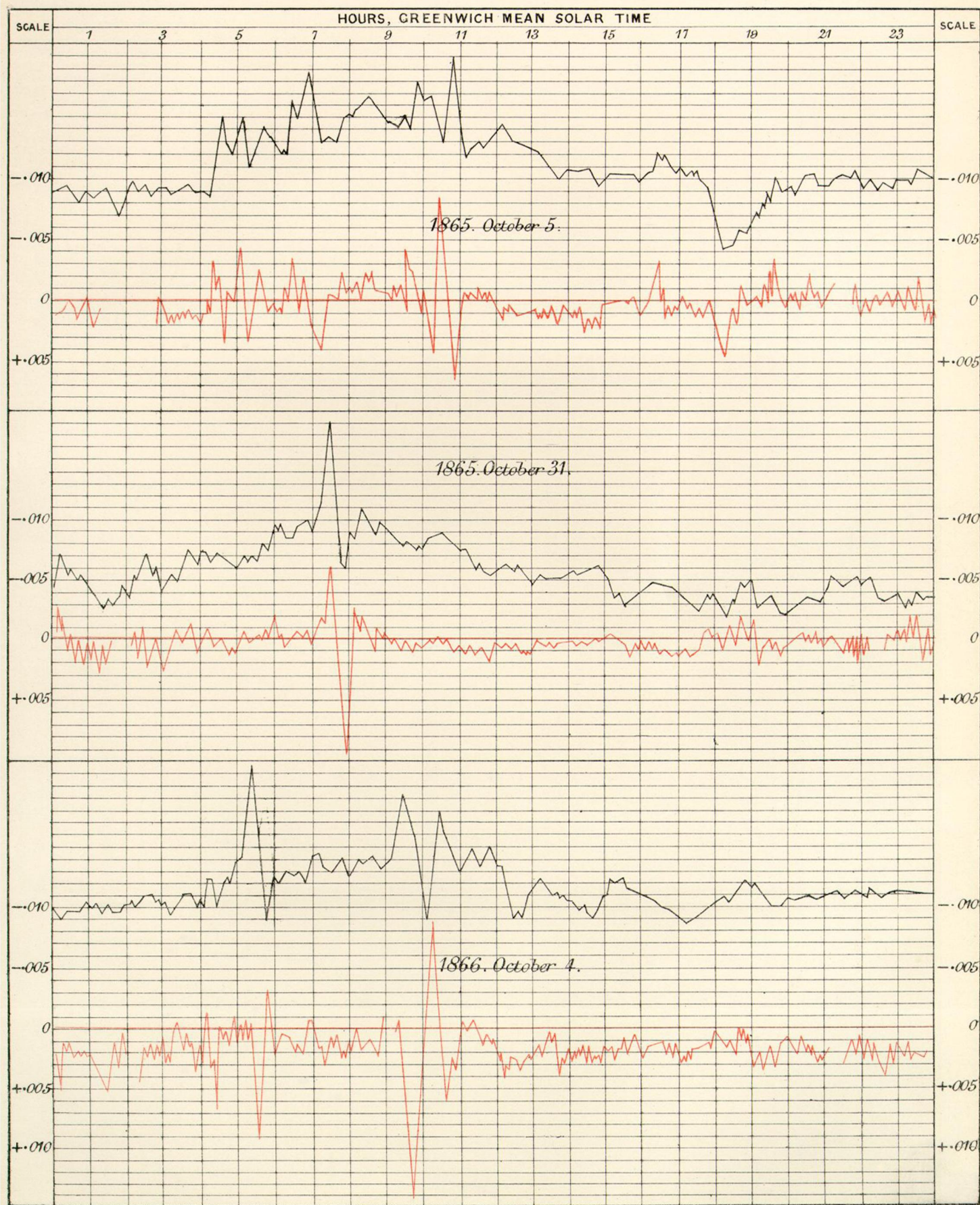
At present we are unable to say whether the records of the galvanic currents throw any light on the origin of the diurnal variations of the magnetic elements.

On one point, however, we seem to be able to speak with confidence; they do not explain the existence of the principal part of terrestrial magnetism. The hypothesis of Professor BARLOW in the *Philosophical Transactions*, 1831, plausible as it undoubtedly was, is not supported by the discovery of galvanic currents competent to explain the earth's general magnetism.

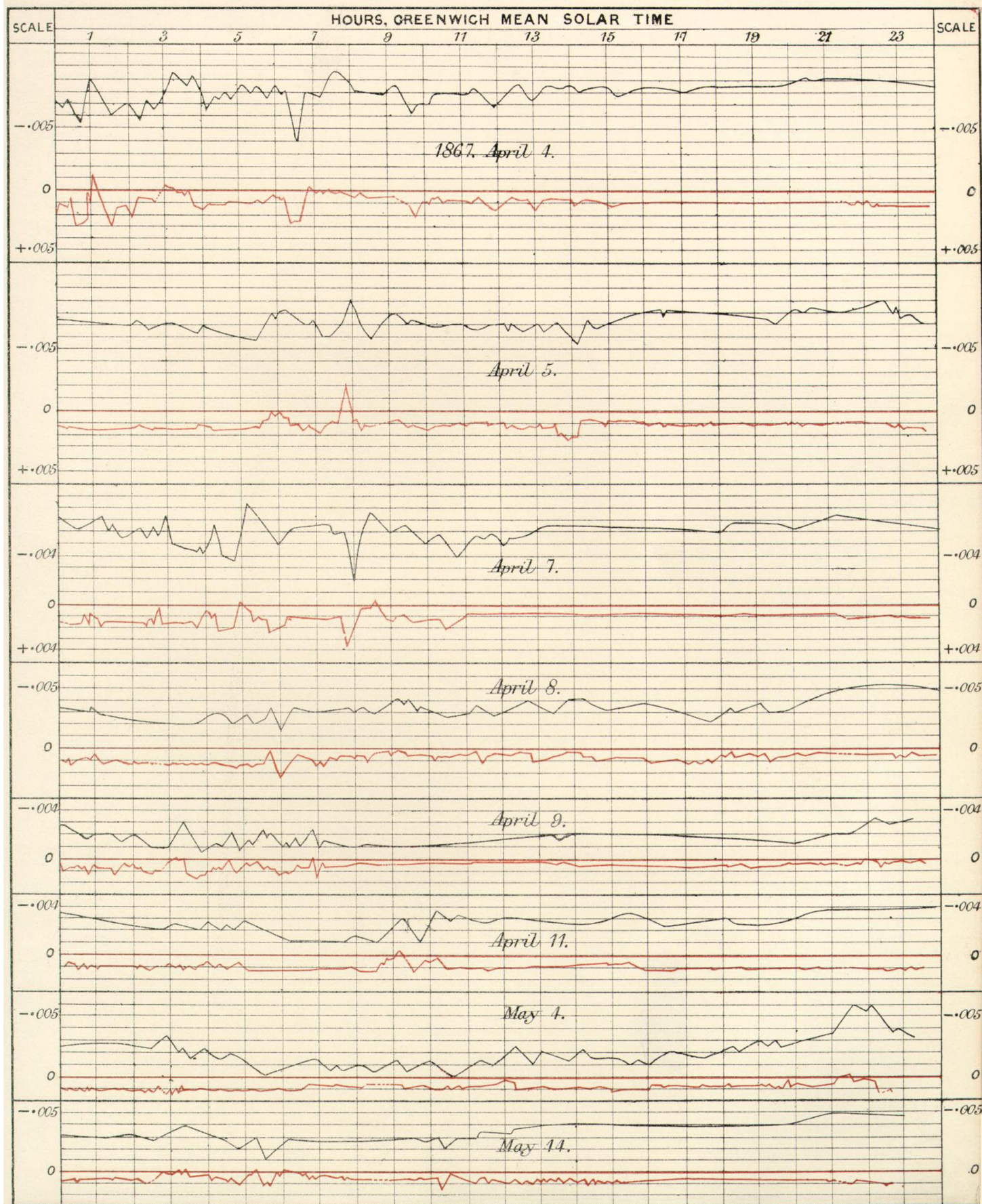
N. FORCE BY MAGNETOMETER.
N. FORCE BY EARTH CURRENTS.



W. FORCE BY MAGNETOMETER.
W. FORCE BY EARTH CURRENTS.



N. FORCE BY MAGNETOMETER.
N. FORCE BY EARTH CURRENTS.



HOURS, GREENWICH MEAN SOLAR TIME

SCALE

1 3 5 7 9 11 13 15 17 19 21 23

SCALE

1867. April 4.

April 5.

April 7.

April 8.

April 9.

April 11.

May 4.

May 14.

HOURS, GREENWICH MEAN SOLAR TIME.

SCALE

1 3 5 7 9 11 13 15 17 19 21 23

SCALE

1867. May 28.

May 31.

June 1.

June 2.

June 7.

June 24.

W. FORCE BY MAGNETOMETER.
W. FORCE BY EARTH CURRENTS.

